

Latest Result On Rare Kaon Decay From E787

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XXXVIIth RENCONTRES DE MORIOND

- Motivation of the E787 experiment
- The E787 experiment
- Background study
- Search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal
- Measurement of branching ratio
- Contribution to the CKM Matrix
- E949 and KOPIO experiments
- Conclusions

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The E787 Collaboration

- Canada
TRIUMF, Alberta
- U.S.
BNL, Princeton
- Japan
KEK, Fukui, Osaka

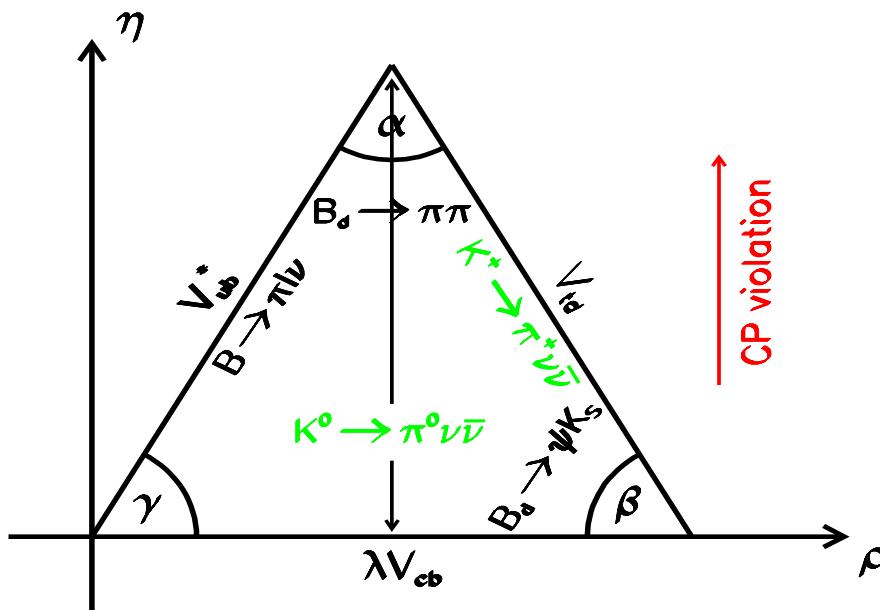
1 Motivation of E787 Experiment

1.1 CKM matrix and CP violation

$$V = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq \begin{bmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

CP violation: $J_{cp} \approx A^2\lambda^6\eta \neq 0$
 $\eta = 0 \Rightarrow \text{no CP in SM}$

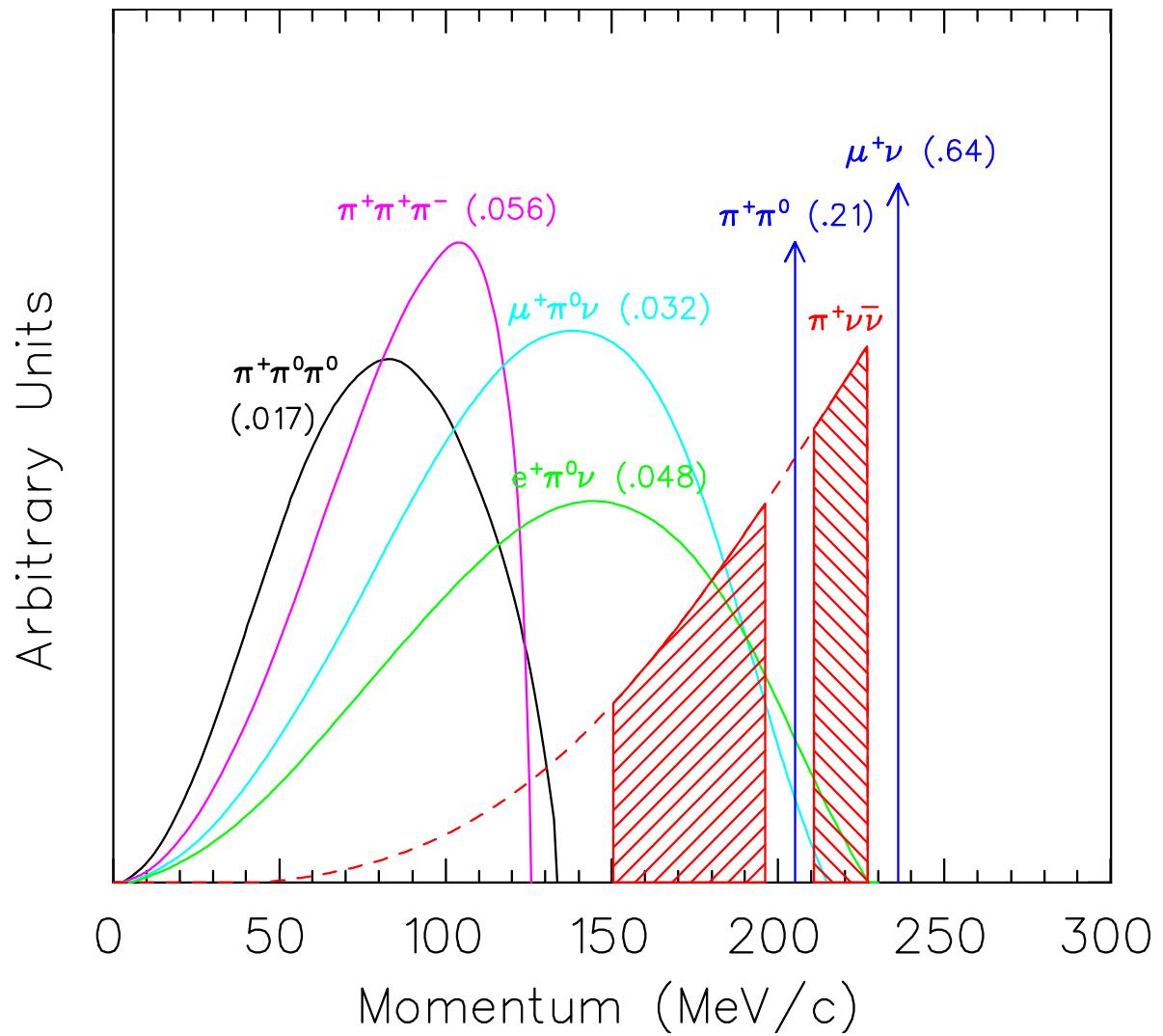
1.2 $K \rightarrow \pi\nu\bar{\nu}$ and CKM matrix



$K^+ \rightarrow \pi^+\nu\bar{\nu}$: E787/E949
 $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$: KOPIO

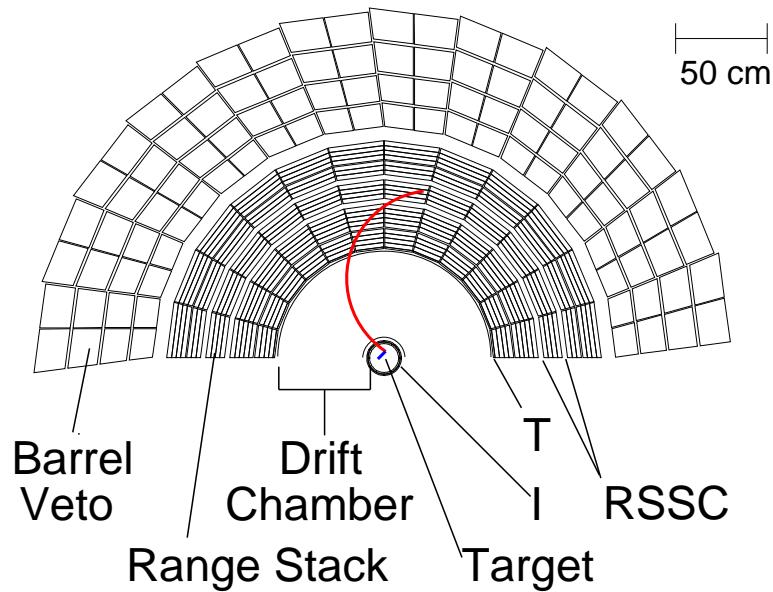
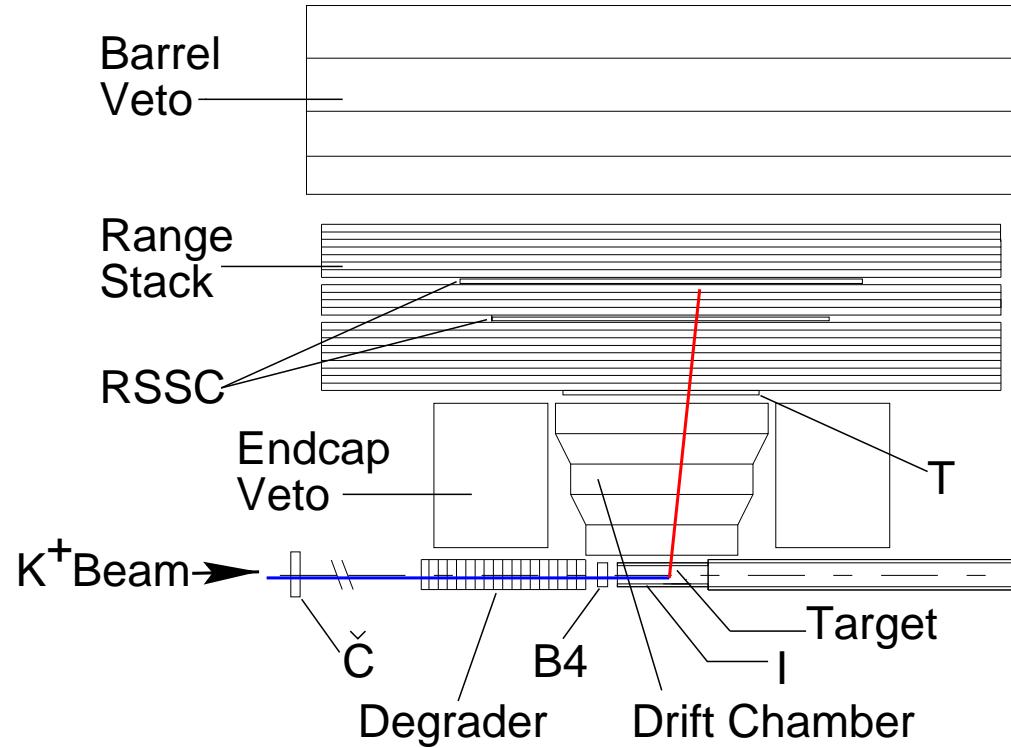
2 The E787 experiment

2.1 E787 is a K-stop experiment



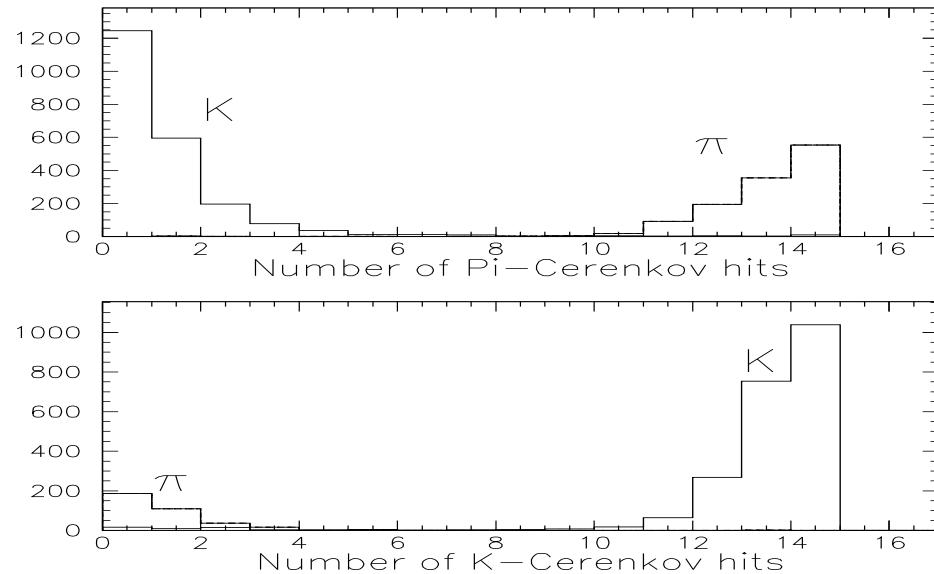
- Well defined kinematic features
- Two regions for the search of $K^+ \rightarrow \pi^+\nu\bar{\nu}$

2.2 The E787 detector

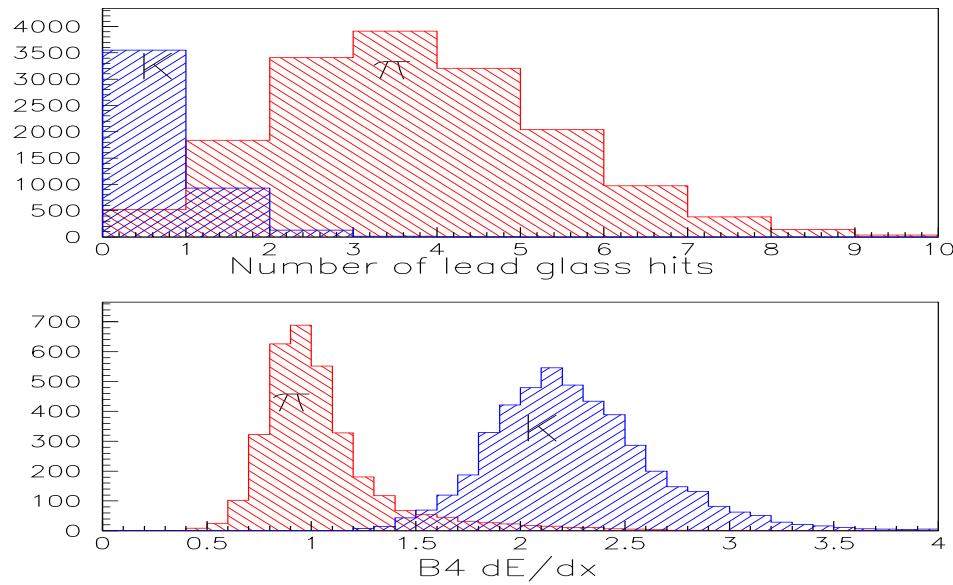


2.3 K/π separation by beam counters

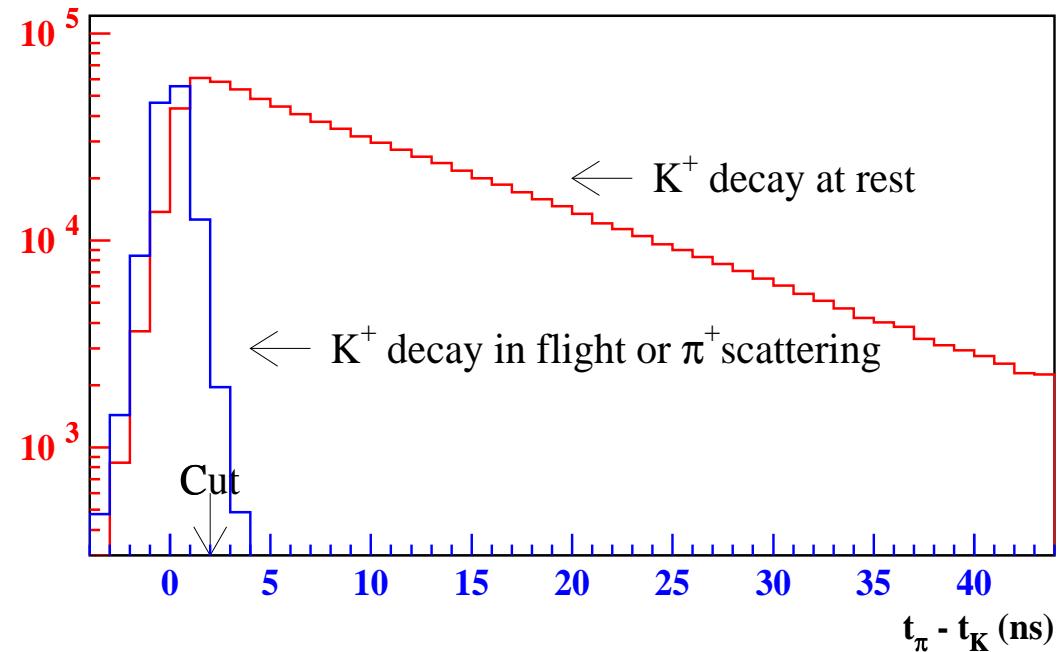
2.3.1 Čerenkov counter



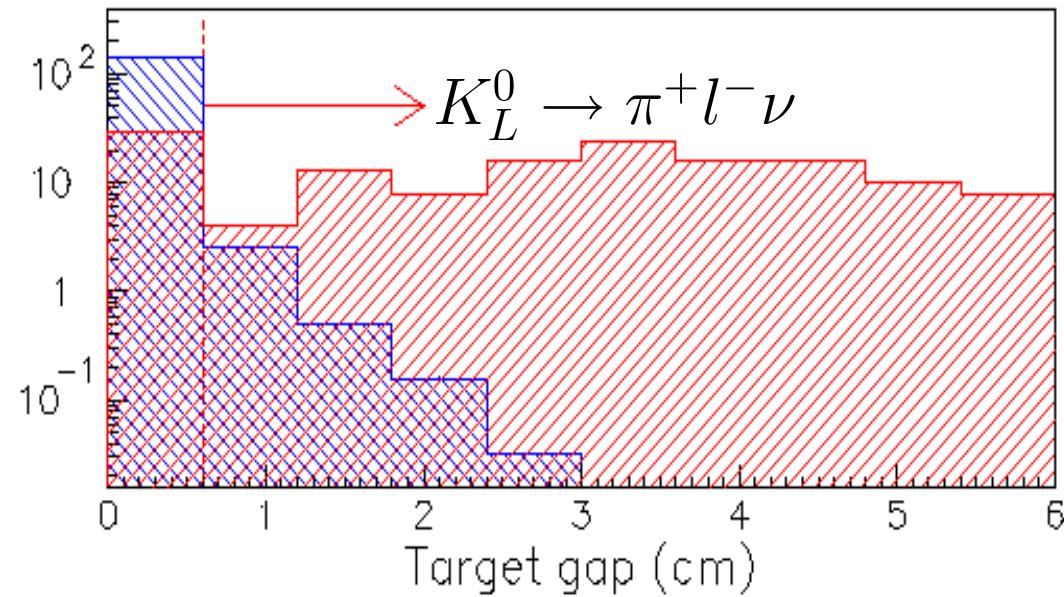
2.3.2 B4 hodoscope and lead glass



2.4 Delay coincidence

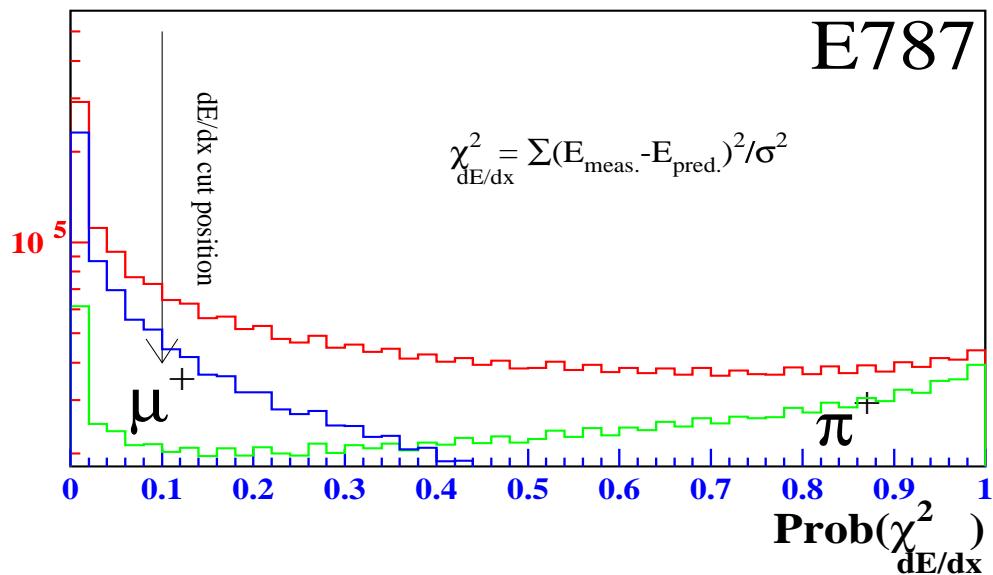
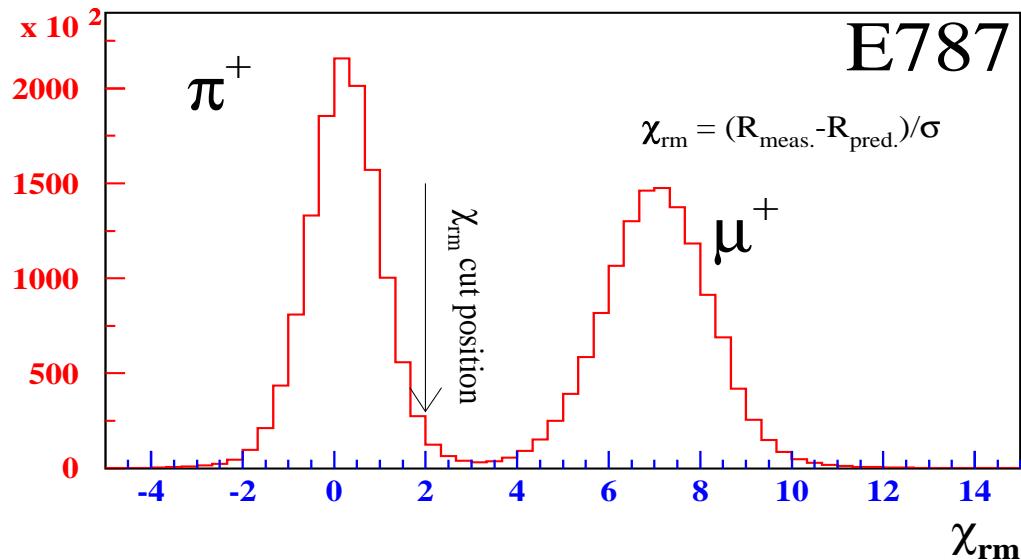


2.5 Target fiber granularity

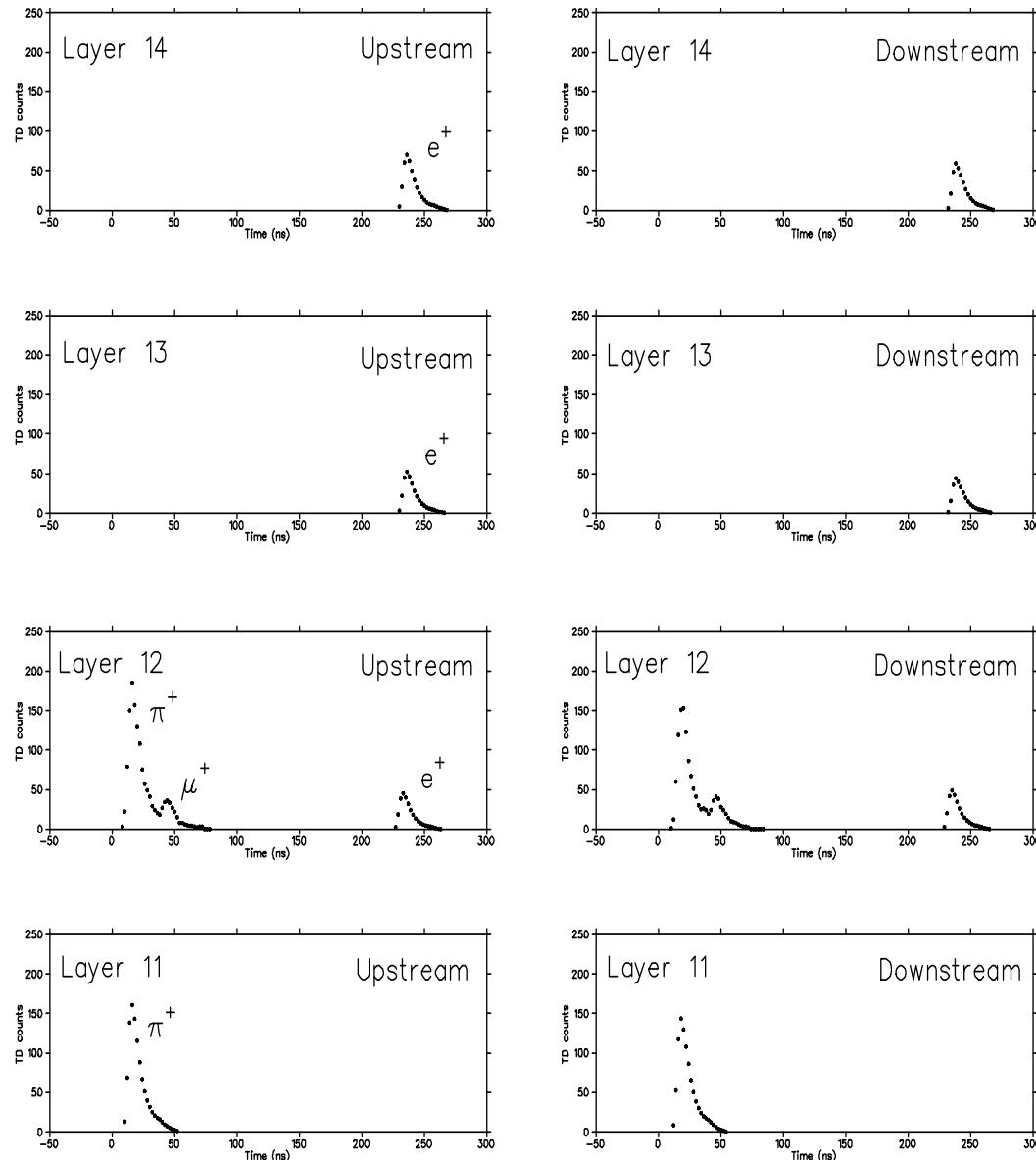


2.6 Kinematic measurable

- **Momentum resolution** $\sigma_P/P \sim 1.1\%$.
- **Range resolution** $\sigma_R/R \sim 2.9\%$.
- **Energy resolution** $\sigma_E/\sqrt{E(\text{GeV})} \sim 1.0\%$.



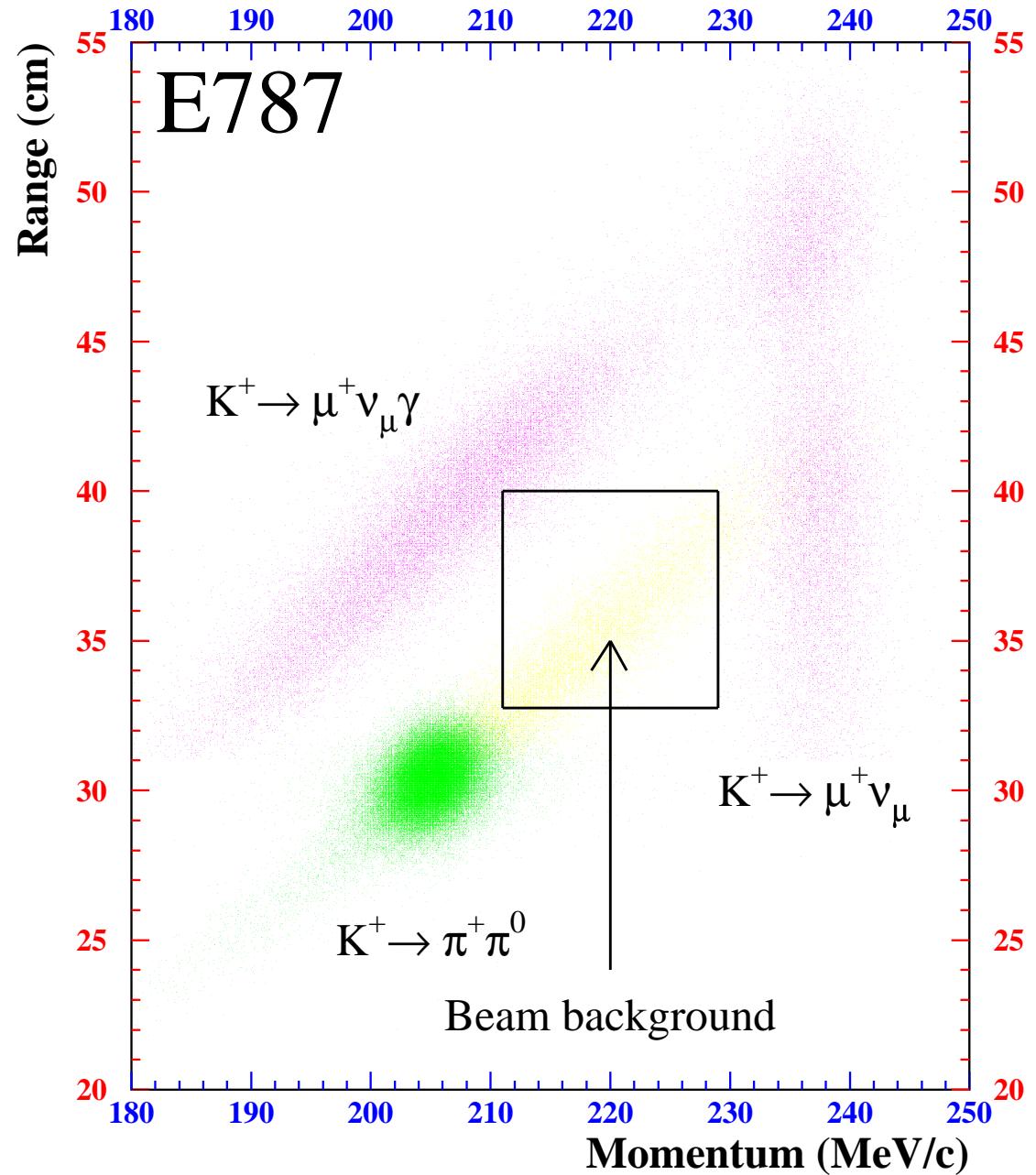
2.7 500 MHz transient digitizers (TD)



- Pulse shapes from both ends of the plastic scintillators.
- Ability to identify the $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay sequence
- Providing an independent PID

3 Background Study

3.1 Backgrounds in $\pi^+\nu\bar{\nu}(1)$ analysis



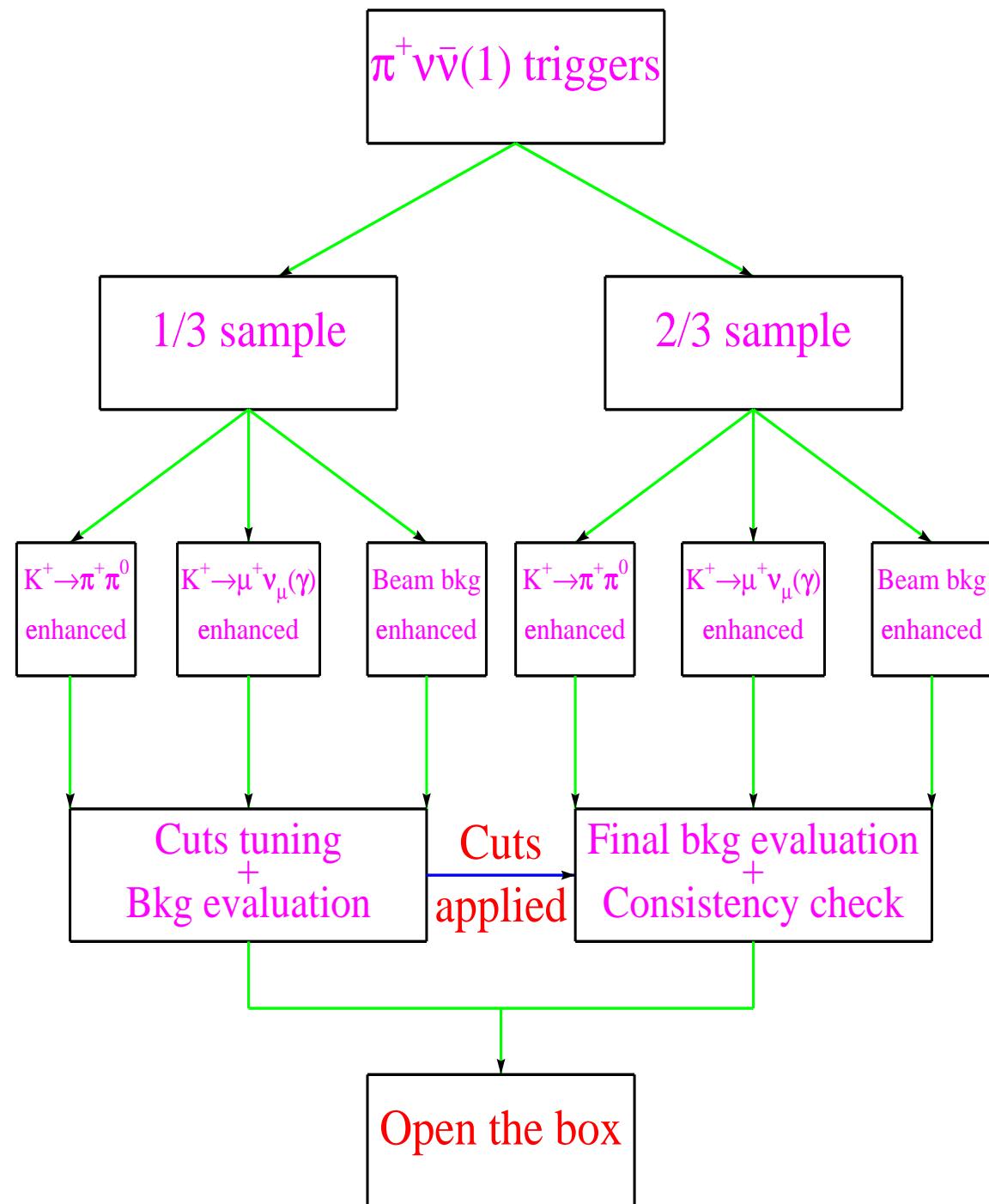
3.2 Background mechanisms

Background type	Background mechanism
$K^+ \rightarrow \mu^+ \nu_\mu (\gamma)$	μ^+ mis-id as π^+ kinematics mismeasured (photon missed)
$K^+ \rightarrow \pi^+ \pi^0$	kinematics mismeasured photons missed
Beam backgrounds	incoming π^+ mis-id as K^+ π^+ fakes K^+ decay at rest K^+ decay-in-flight
$K^+ n \rightarrow K^0 p$ (CEX) $K_L^0 \rightarrow \pi^+ l^- \nu$	Two beam particles K_L^0 decays in target lepton missed

3.3 Background suppression

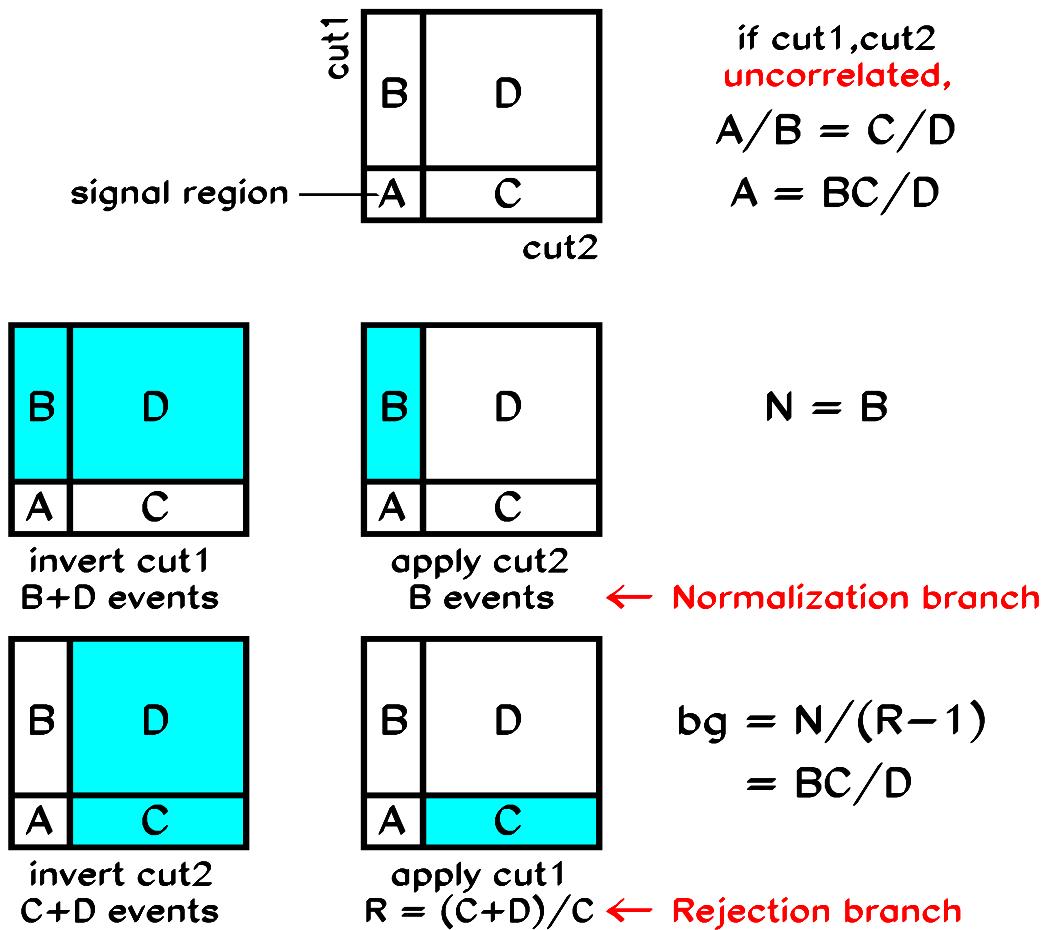
Bkg	Kin.	PV	PID	1 tr.	$\check{C}_{K,\pi}$	DC
$\mu^+ \nu_\mu$	X		X			
$\pi^+ \pi^0$	X	X				
$\mu^+ \nu_\mu \gamma$	X	X	X			
Beam bkg			X		X	X
CEX				X		X

3.4 $\pi^+ \nu\bar{\nu}$ data analysis



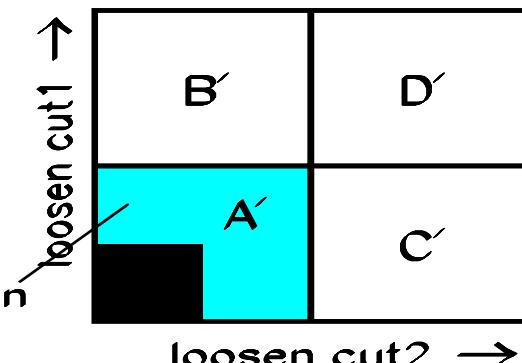
3.5 Bifurcated Analyses

3.5.1 How does it work?



3.5.2 How can we check the correlation?

predict
 $bg' = B'C'/D' - BC/D$
 mask out box
 and observe
 outside-the-box region



3.6 Background levels

3.6.1 Cuts used for bifurcation analyses

Bkg	CUT1	CUT2
$\pi^+ \pi^0$	Photo veto	Kinematic cuts
$\mu^+ \nu_\mu (\gamma)$	RS TD PID	Kinematic cuts
1BM	Target timings	B4 dE/dx cuts
2BM	BWPC cuts	B4 2-hit cuts

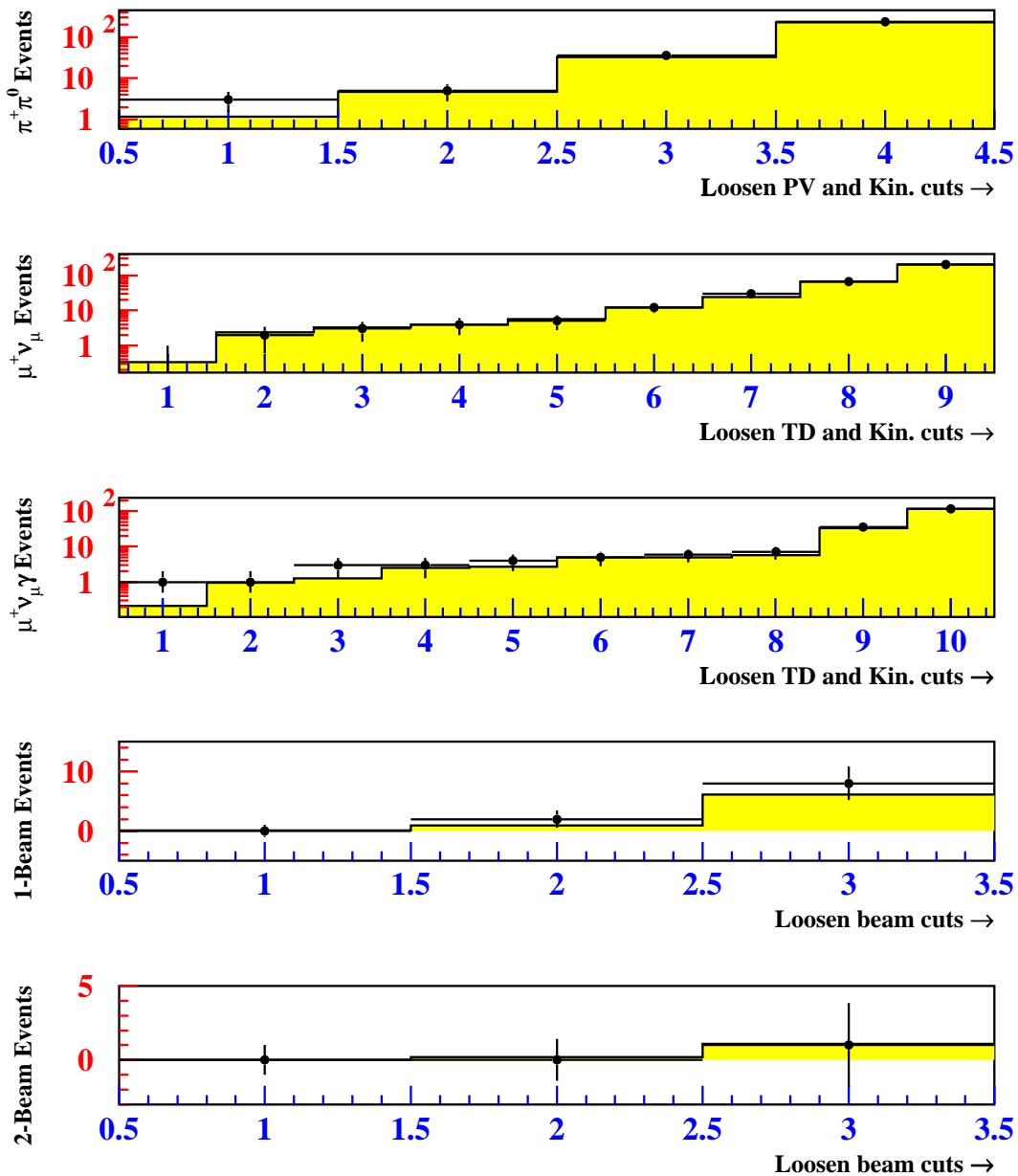
3.6.2 Final background estimates

Bkg	1995-7	1998
$\pi^+ \pi^0$	0.0216 ± 0.0050	$0.0120^{+0.0031}_{-0.0042}$
$\mu^+ \nu_\mu$		0.0092 ± 0.0067
$\mu^+ \nu_\mu \gamma$		0.0245 ± 0.0155
$\mu^+ \nu_\mu (\gamma)$	0.0282 ± 0.0098	$0.0337^{+0.0435}_{-0.0240}$
1BM	0.0054 ± 0.0042	0.0039 ± 0.0012
2BM	0.0157 ± 0.0149	0.0004 ± 0.0001
CEX	0.0096 ± 0.0068	$0.0157^{+0.0050}_{-0.0044}$
Total	0.0804 ± 0.0201	$0.0657^{+0.0438}_{-0.0248}$

– CEX bkg level estimated by M.C.

Total background level is estimated
to be 0.15 event inside the BOX.

3.7 Check for the correlation



- The predicted agree with the observed.
- No correlation observed.

3.8 Consistency check

Bkg	1/3 1998	2/3 1998
$\pi^+\pi^0$	0.009 ± 0.009	$0.0120^{+0.0031}_{-0.0042}$
$\mu^+\nu_\mu(\gamma)$	0.025 ± 0.025	$0.0337^{+0.0435}_{-0.0240}$
1BM	0.003 ± 0.002	0.0039 ± 0.0012
2BM	0.004 ± 0.003	0.0004 ± 0.0001
CEX	$0.0157^{+0.0050}_{-0.0044}$	$0.0157^{+0.0050}_{-0.0044}$
Total	0.057 ± 0.027	$0.0657^{+0.0438}_{-0.0248}$

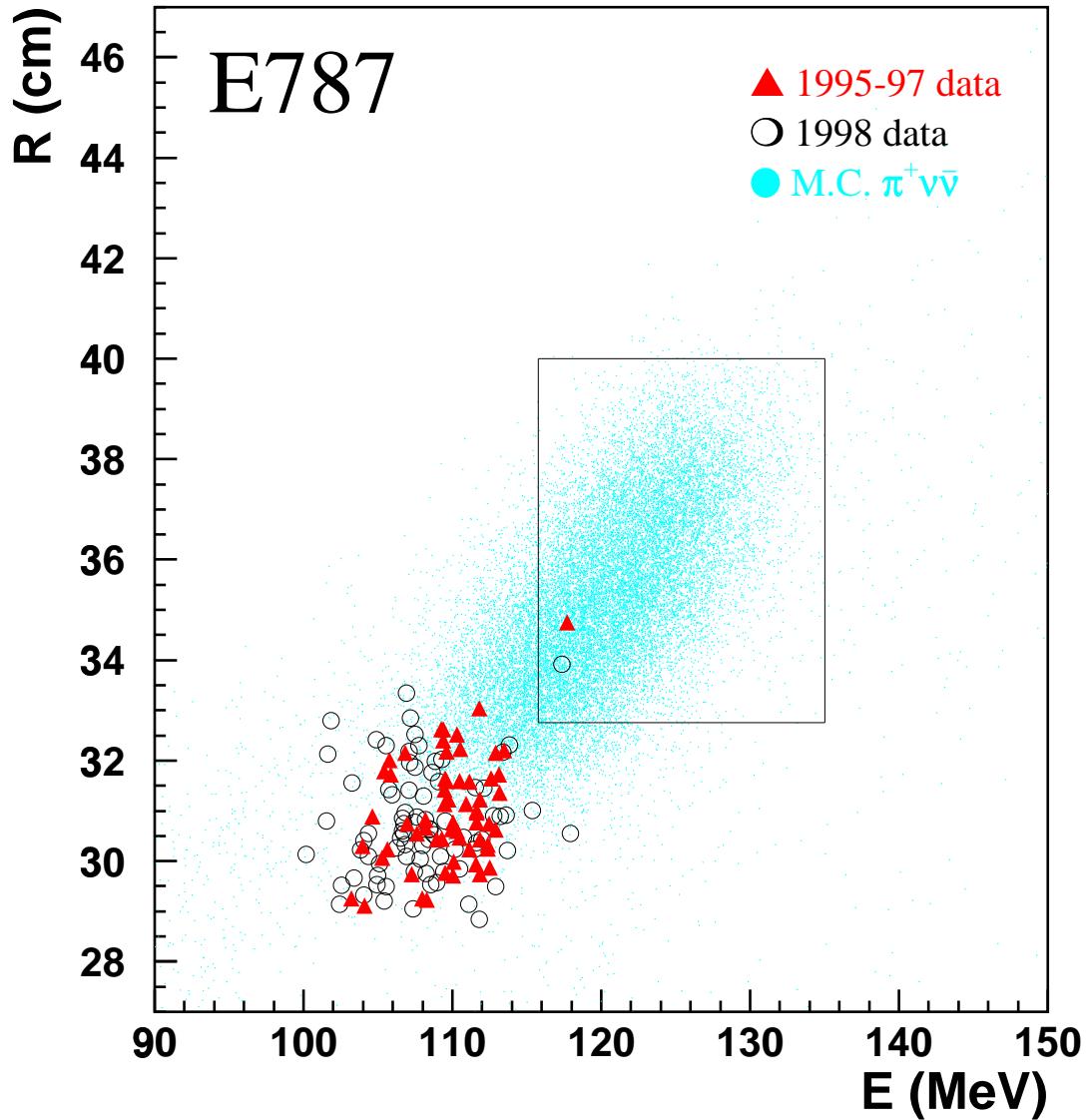
Bkg	1/3 1995-97	2/3 1995-97
$\pi^+\pi^0$	0.0224 ± 0.0074	0.0216 ± 0.0050
$\mu^+\nu_\mu(\gamma)$	0.0291 ± 0.0095	0.0282 ± 0.0098
1BM	0.0091 ± 0.0066	0.0054 ± 0.0042
2BM	0.0073 ± 0.0087	0.0157 ± 0.0149
CEX	0.0096 ± 0.0068	0.0096 ± 0.0068
Total	0.0764 ± 0.0177	0.0804 ± 0.0201

We are ready for opening the BOX.

God bless E787!

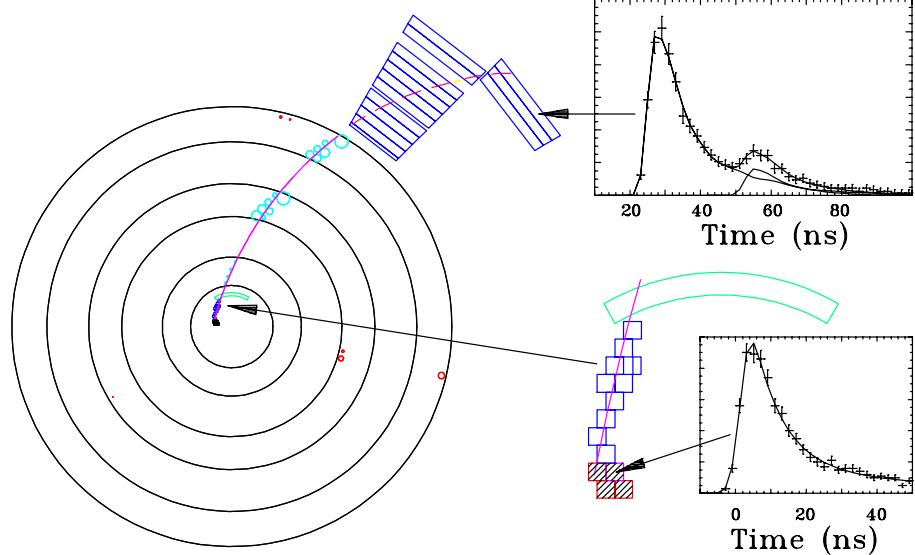
Open the Box and the Answer

is ...

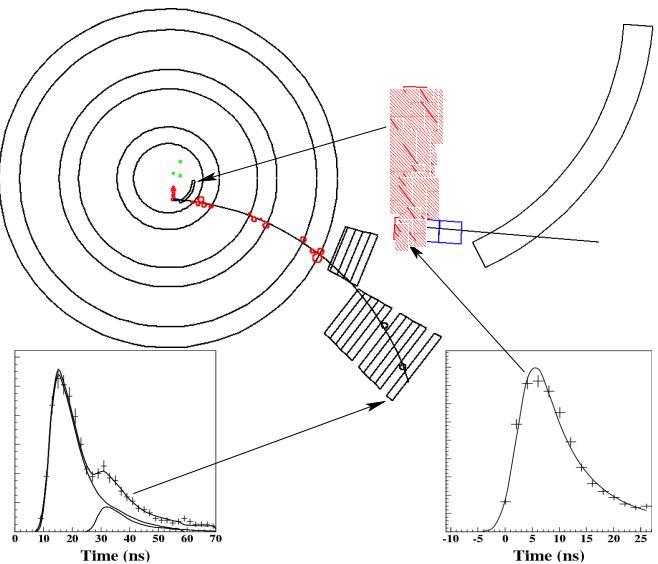


The $\pi^+ \nu \bar{\nu}$ events look ...

1995 Event

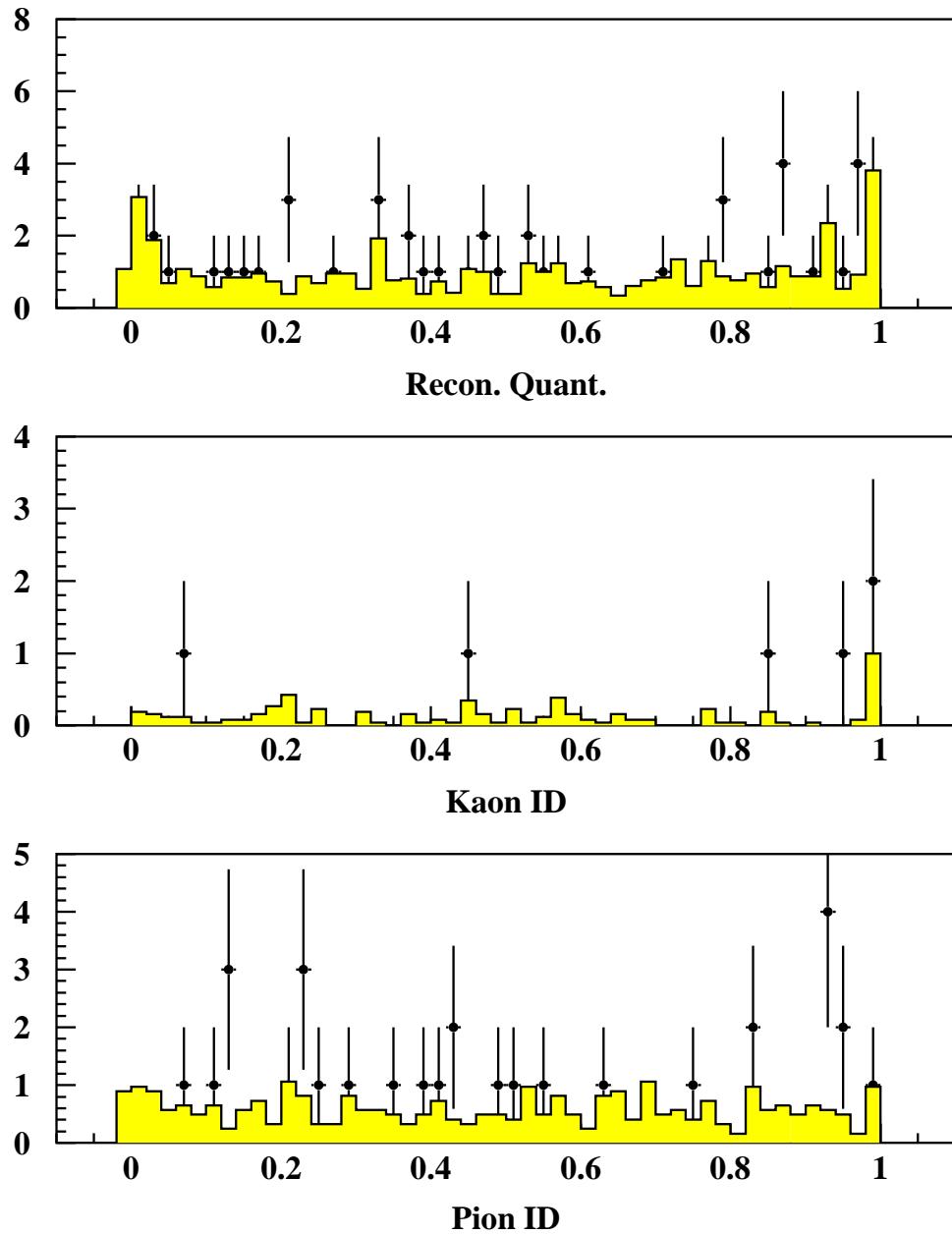


1998 Event



... almost flawless!

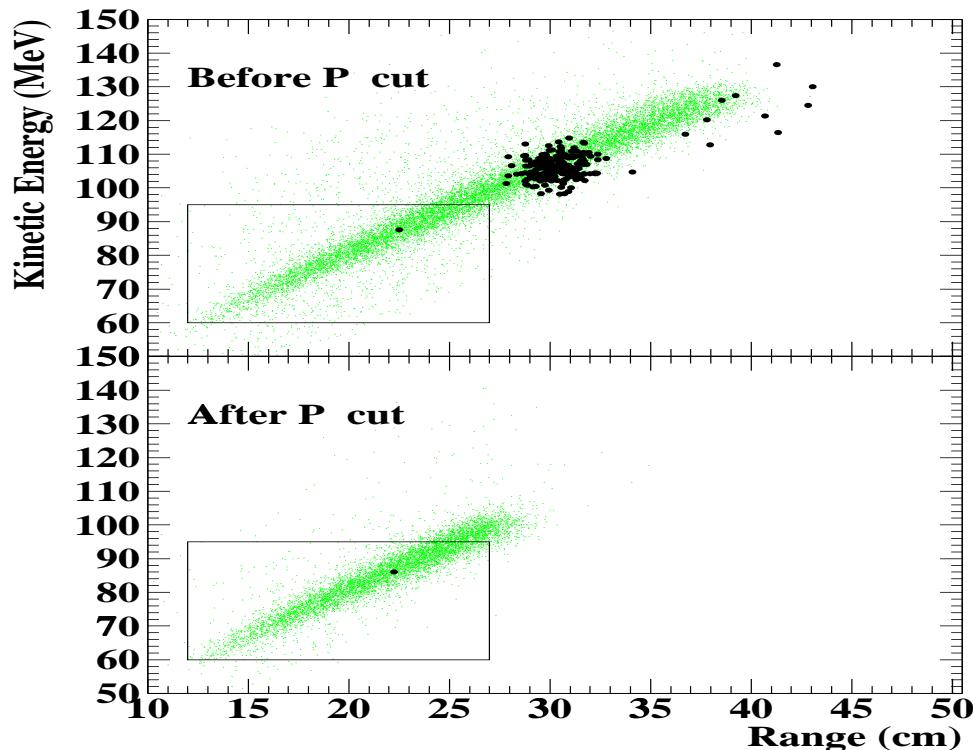
The probabilities of 1998 event look ...



... also ok!

3.9 Signal search below $\pi^+\pi^0$ peak

- Total background level for 1996 data
 $\sim 0.73 \pm 0.18$, dominated by $K^+ \rightarrow \pi^+\pi^0$
with π^+ scattered in target 0.63 ± 0.17
- Open the box...



...consistent with the bkg estimated

- This search is limited by background in E787 and will be improved in E949 with more powerful photon veto

4 Measurement of Branching Ratio

4.1 Acceptance study

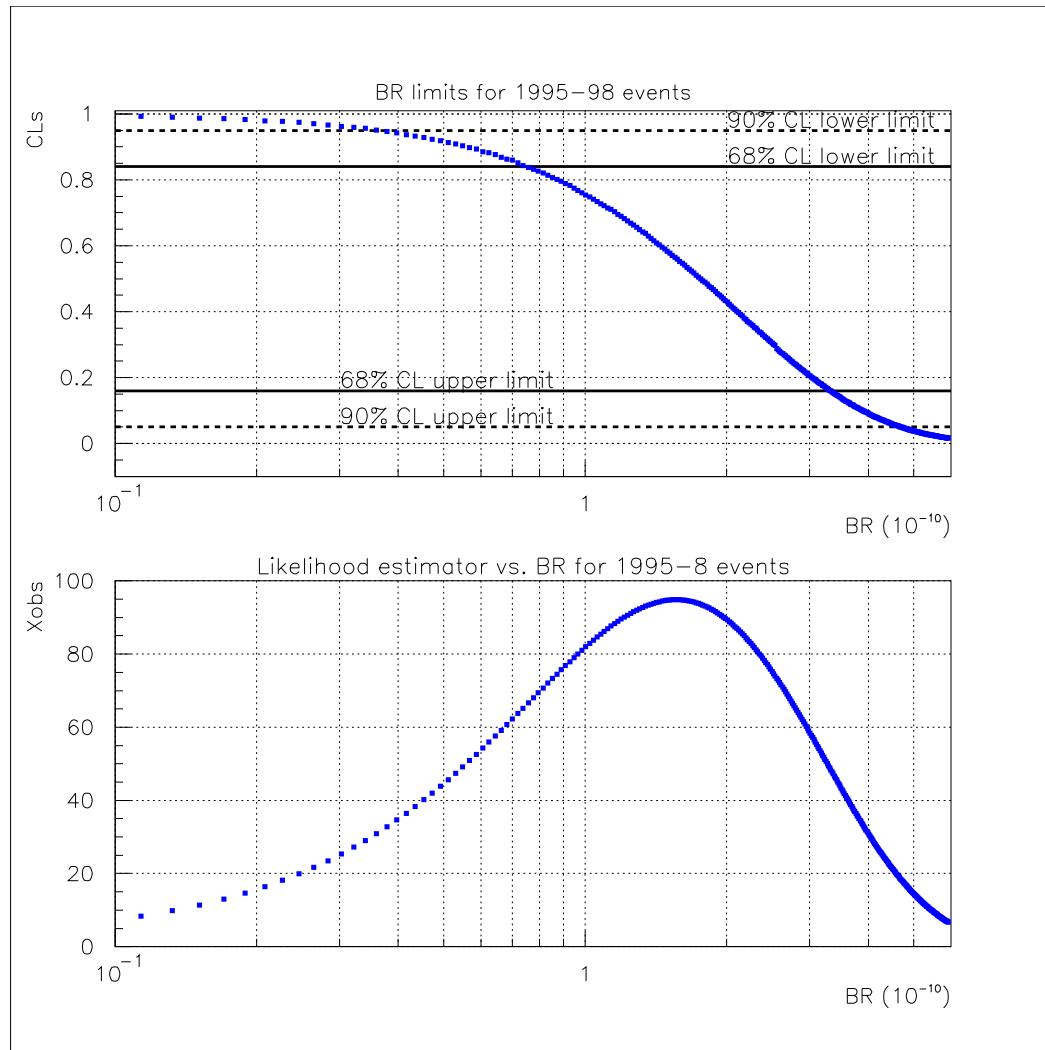
- Acceptance is estimated by $\mu^+ \nu_\mu$, $\pi^+ \pi^0$, π^+ -scattering monitors and M.C. $\pi^+ \nu \bar{\nu}$

Category	1995-97	1998
K^+ stop efficiency	0.704	0.702
K^+ decay after 2 ns	0.850	0.851
$\pi^+ \nu \bar{\nu}$ phase space	0.155	0.136
Solid angle acceptance	0.407	0.409
π^+ nucl. interaction	0.513	0.527
Reconstruction efficiency	0.959	0.969
Other kinematic constraints	0.665	0.554
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay acc.	0.306	0.392
Beam and target analysis	0.699	0.706
Accidental loss	0.785	0.751
Total acceptance	0.0021	0.0020
Total K^+ triggers ($\times 10^{12}$)	3.2	2.7
Sensitivity ($\times 10^{-10}$)	1.50	1.89
# of signal events	1	1
$\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) (\times 10^{-10})$	$1.5^{+3.5}_{-1.2}$	$1.9^{+4.4}_{-1.5}$

- The validity is checked with $\text{Br}(K^+ \rightarrow \pi^+ \pi^0)$

$$\begin{aligned}\text{Br}(K^+ \rightarrow \pi^+ \pi^0) &= 0.208 \pm 0.003_{\text{stat.}} \quad (1995-97) \\ &= 0.217 \pm 0.003_{\text{stat.}} \quad (1998) \\ &= 0.212 \pm 0.001 \quad (\text{PDG})\end{aligned}$$

4.2 Statistical analysis of $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

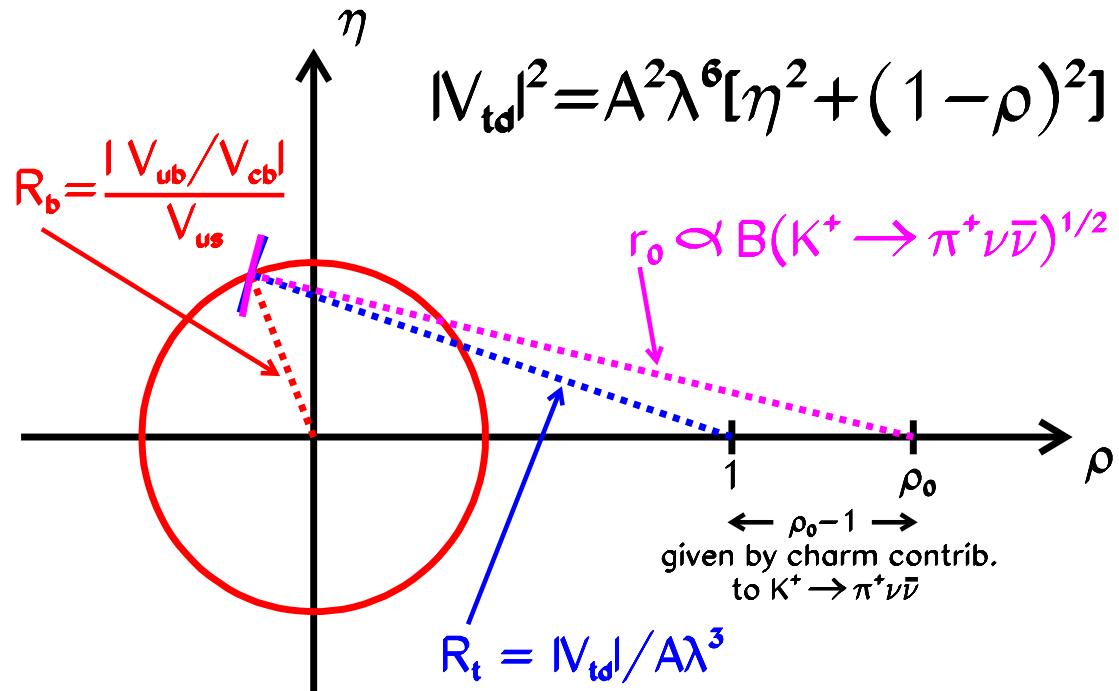


T. Junk, NIM A434, 435(1999)

$$\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

5 Contribution to the CKM Matrix

- Assume unitarity, $\bar{m}_t(m_t) = 166 \pm 5 \text{ GeV}/c^2$, $M_W = 80.41 \text{ GeV}/c^2$ and $V_{cb} = 0.041 \pm 0.002$



$$0.007 < |V_{td}| < 0.030 \text{ (68% C.L.)},$$

independent of B system (V_{ub}) or ϵ_K .

- Also given are the limits on

$$2.9 \times 10^{-4} < |\lambda_t \equiv V_{ts}^* V_{td}| < 1.2 \times 10^{-3}$$

$$-0.88 \times 10^{-3} < \operatorname{Re}(\lambda_t) < 1.2 \times 10^{-3}$$

$$\operatorname{Im}(\lambda_t) < 1.0 \times 10^{-3}$$

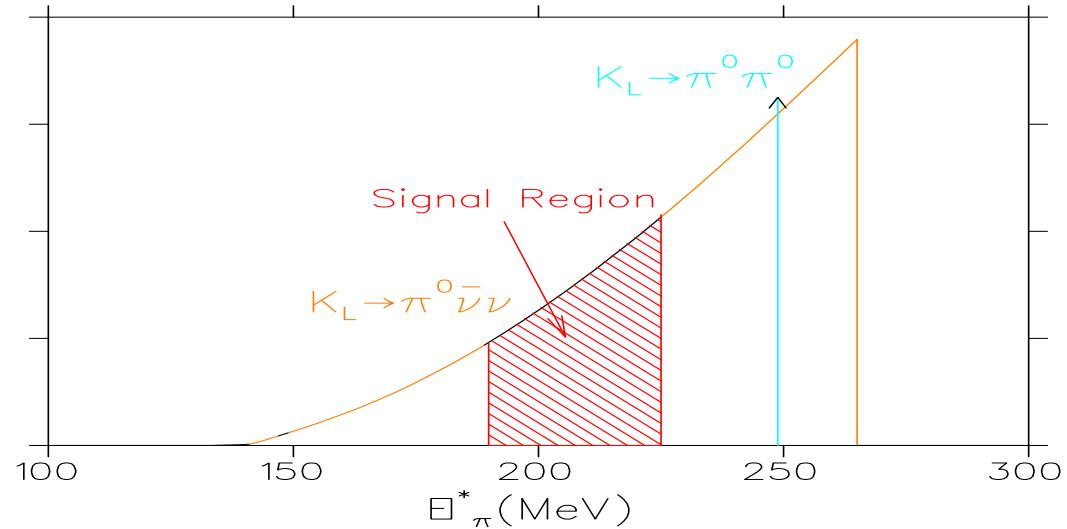
6 E949 and KOPIO experiments

6.1 The status of E949 experiment

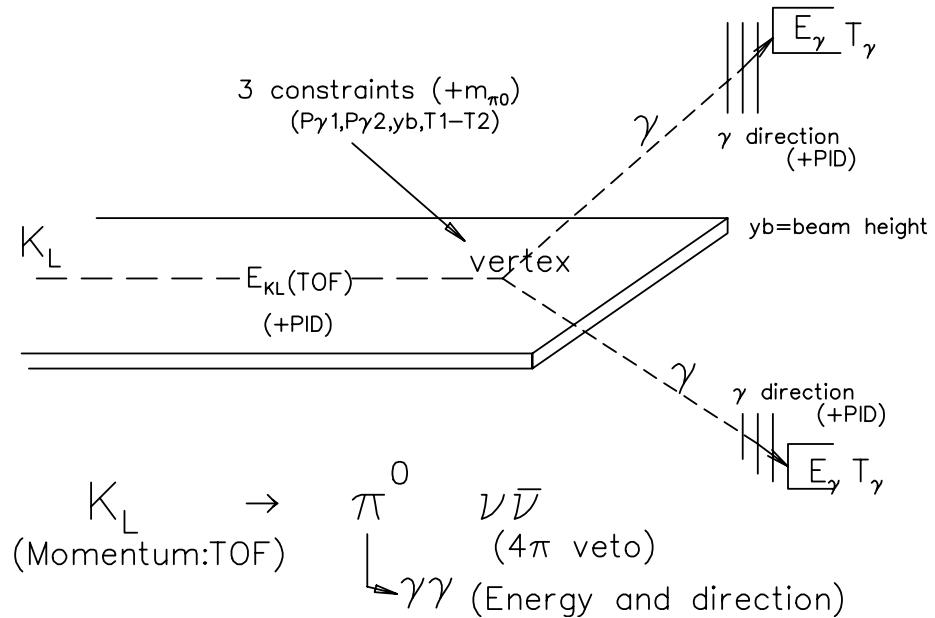
- Collaboration extended (**FNAL, IHEP, INR, Kyoto and UNM**)
- E949 is successor of E787 with a number of changes:
 - Proton flux $15 \times 10^{12} \rightarrow 65 \times 10^{12}$ p/spill
 - New degrader and B4 hodoscope (beam background)
 - Last 3 RS layers replaced with the Barrel Veto Liner (photon veto)
 - New electronics added for UTC and RSSC (tracking efficiency and position resolutions)
 - RS 1-5 layers replaced (timing and dE/dx resolutions)
 - RS monitor system (energy resolution)
 - Trigger upgrade (dead time and rejection)
 - DAQ upgrade (dead time and high rate capability)
- Aimed at increasing **sensitivity** $< 10^{-11}$ and rejection to background (**a factor of two more photon veto**)
- Data taking is still ongoing

6.2 The future KOPIO experiment

- Search for $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$



- Measure all initial & final state quantities



- Measure Br to $\sim 15\%$ with $S/N \sim 2$

7 Conclusions

A decade long search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ by E787

Two signal events observed!

$$\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.57^{+1.75}_{-0.82} \times 10^{-10}$$

